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Stellar oxygen abundances. IV: Systematic effects on oxygen abundances derived from the 6300 A (O I) and 7774 A O I lines

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STELLAR OXYGEN ABUNDANCES. IV. SYSTEMATIC EFFECTS ON OXYGEN ABUNDANCES DERIVED FROM THE 6300 Å [O I] AND 7774 Å O I LINES

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ABSTRACT

We consider potential systematic effects on oxygen abundances derived from the 6300 Å [O I] line and the 7774 Å O I triplet. Our solar intensity spectra of the 7774 Å triplet confirm previous results which indicate a discrepancy between the observed equivalent widths of Altrock [Sol. Phys. 5, 260 (1968)] and the values predicted by LTE and recent NLTE models. However, this disagreement (at low μ) does not seem to affect the solar O abundance as derived from *flux* spectra. We derive O abundances for a selection of relatively metal-rich F and G dwarfs from both the 6300 Å [O I] line and 7774 Å O I triplet and detail the various uncertainties which enter into the analyses. Minimizing possible systematic effects to the extent possible, we find for $T_{\rm eff} \lesssim 6200-6300$ K no systematic difference between the 6300 and 7774 Å abundances. For $T_{\rm eff} \gtrsim 6200-6300$ K, however, the 7774 Å abundances are substantially larger than the 6300 Å abundances. This agreement in O abundances from the two features at cooler $T_{\rm eff}$ conflicts with that of others and we suggest that the discrepancy may be due to the different model atmospheres utilized. If recently proposed, hotter $T_{\rm eff}$ values for metal-poor dwarfs are correct, then there appears to be no discrepancy between the 6300 Å abundances of metal-poor giants or dwarfs and the 7774 Å abundances for dwarfs. This would seem to rule out substantial LTE departures or atmospheric inhomogeneity effects skewing metal-poor O abundances from the 7774 Å triplet (for cooler stars having low metallicity anyway). Given the repeated inability of authors to reproduce each others' O abundances from the 6300 Å [O I] line and the uncertainties in the solar equivalent width, we question the usual assumption that the 6300 Å [O I] abundances are more reliable than those from the permitted triplet.

1. INTRODUCTION

The O abundance and [O/Fe] ratio of stellar atmospheres/interiors are important parameters of renewed interest. O abundances provide clues and constraints concerning galactic chemical evolution (Wheeler *et al.* 1989) and galaxy formation (Gilmore *et al.* 1989; Wyse & Gilmore 1992). Stellar evolutionary models, which are used to produce isochrones for globular cluster age derivations, may be affected by the choice of [O/Fe] ratio. Unfortunately, stellar O abundances (particularly in halo stars) are presently ill determined. Analysis of the 6300 Å [O I] line in halo *giants* indicates that [O/Fe]$\sim$+0.4 to +0.5 (e.g., Barbuy & Erdelyi-Mendes 1989; Barbuy 1990; Bessell *et al.* 1991). Abia & Rebolo (1989) determined O abundances in halo *dwarfs* using the 7774 Å O I triplet and found that [O/Fe] increased with decreasing metallicity, reaching $\sim$+1.2 for stars with [Fe/H] $\leqslant -2.5$. The halo dwarf abundances of Boesgaard & King (1993), whose parameter scale was similar to Abia & Rebolo's, show the same behavior, though the mean [O/Fe] ratio is $\sim$0.2 dex lower on average.

It has been repeatedly suggested (e.g., Kiselman 1991; Spiesman & Wallerstein 1991; Spite & Spite 1991; Nissen & Edvardsson 1992, hereafter referred to as NE92) that the large discrepancy in the [O/Fe] ratios of metal-poor giants and dwarfs could be caused by either (or both): (a) NLTE effects on the high-excitation 7774 Å O I triplet; (b) thermal inhomogeneities, again affecting the 7774 Å lines, that are not accounted for in model atmospheres. Evidence of systematic effects in the 7774 Å abundances comes from the analysis of the 6300 Å [O I] line (which is not thought to be subject to the effects of NLTE departures or thermal inhomogeneities; Altrock 1968; Lambert 1978; Kiselman 1991) in halo dwarfs. Spiesman & Wallerstein (1991) found [O/Fe] =+0.3 and +0.4 for two dwarfs having [Fe/H]=-1.74 and -1.43. Spite & Spite (1991) found [O/Fe]=+0.48 and +0.59 for two dwarfs having [Fe/H]=-1.4 and -1.6. These [O/Fe] values are significantly lower than the values derived by Abia & Rebolo (1989) for halo dwarfs. NE92, in their analysis of 23 metal-rich F and G dwarfs, also found that the O abundances derived from the permitted triplet are larger than those derived from the forbidden line (by $\sim$0.2 dex at [Fe/H]=-0.8) and that this difference increases with decreasing metallicity.

Kiselman (1991) theoretically investigated NLTE effects on O abundances derived from the 7774 Å triplet. The top and middle panels of his Fig. 4 indicate that his NLTE calculations are able to reduce the [O/Fe] ratios of the most

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metal-poor stars by ~0.4 dex, bringing them into closer agreement with the ratios derived using the 6300 Å [O I] line. However, the solar disk equivalent widths of the 7774 Å O I lines predicted by Kiselman's (1991) NLTE models conflict with the observations of Altrock (1968). Kiselman's (1991) LTE calculations are in good agreement with the solar disk center equivalent widths, but the shape of the variation with the cosine angle, μ, across the solar disk is not as well reproduced as with the NLTE models. This confusing situation is exacerbated by the NLTE calculations of Abia & Rebolo (1989), Tomkin *et al.* (1992; hereafter referred to as TLLS), and Takeda (1994), which all indicate NLTE effects on O abundances derived from the 7774 Å O I triplet are very small (a few hundredths of a dex) for metal-poor dwarfs.

King (1993) proposed an explanation for the larger O abundances of metal-poor stars as derived from the 7774 Å permitted triplet. Accounting for perceived inaccuracies in measured equivalent widths (a result confirmed by TLLS) and metal-poor $T_{\rm eff}$ scales, he found the mean [O/Fe] level derived from the 7774 Å triplet of metal-poor dwarfs ([O/Fe]=+0.53) to be in good agreement with the value deduced from the forbidden line in halo giants ([O/Fe]=+0.46, see King 1994). The small difference between these mean [O/Fe] ratios does not appear to be significant given the uncertainties. There is, however, some possibility it could be due to LTE departures (or thermal inhomogeneities) since the size and magnitude are not inconsistent with recent model calculations.

Here, we address some questions concerning O abundances derived from the 7774 Å permitted triplet and the 6300 Å forbidden line: (1) for the Sun, both LTE and NLTE calculations do not adequately reproduce the center-to-limb variation of the 7774 Å triplet equivalent widths. Can the observational data (e.g., Altrock 1968) be confirmed? (2) What are the sources and magnitudes of uncertainty in O abundances derived from both the permitted and forbidden lines? Do the forbidden lines provide more reliable O abundances? (3) Can the systematic differences, seen by NE92, between the forbidden and permitted line abundances in metal-rich F and G dwarfs be confirmed? (4) The effects of LTE departures on O abundances derived from the 7774 Å lines in early type stars are large and seem unquestionable (e.g., Baschek *et al.* 1977). Is the difference between the 6300 and 7774 Å abundances an increasing function of increasing $T_{\rm eff}$ as NLTE calculations predict (Kiselman 1991) and at what temperatures do these NLTE effects become significant?

2. THE SOLAR CENTER-TO-LIMB VARIATION OF THE 7774 Å O I TRIPLET

2.1 *Observations and Data Reduction*

Solar observations of the 7774 Å O I triplet were conducted on 1993 February 17 at Mees Solar Observatory. The data were obtained with the MCCD imaging spectrograph, which has been described by Penn *et al.* (1991). The MCCD is a spatially scanning instrument consisting of the 0.25 m coronagraph telescope, a 3.0 m coudé spectrograph, and a rapid-writing data storage system. A 300 l/mm echelle grating was used in 7th order with an order sorting filter having a central wavelength of 7757 Å and a bandwidth of 115 Å. This yielded a dispersion of 0.021 Å per pixel and the resolution was set by adjusting the slit width. While adjusting the slit, the device monitoring the width ceased to function. We estimate a slit width of ~2.4 pixels and do know that it was ≤2.6 pixels. The detector was a cooled, UV-coated 384×576 Thompson CCD with 22 μm pixels.

We first located disk center by monitoring the solar image from a video rate CCD camera and associated instrumental encoder readings. Centering was performed in both the N–S and E–W directions. The solar limb position in our images agreed closely with that expected from the centering procedure, thus confirming that the scan sequence across the disk was made along a projection of a great circle rather than along a chord with an origin displaced from disk center. Two 1 s scans were taken at each position, beginning at disk center, then moving south to the limb (with the instrument scanning in the E–W direction), and back to disk center. Four pixel binning was employed in one of the spatial directions. Calibration frames (biases, darks, and flats) were taken before and after the scan sequence. We also obtained five 1 s disk center scans in the midst of the telluric *A* band as a check on scattered light. An order sorting filter centered at 7610 Å with a bandwidth of 360 Å was employed for the *A*-band data.

Preliminary reductions consisted of trimming, removal of the dc-offset level via a mean bias frame, and removal of dark current via a mean dark frame. Unfortunately, flatfielding (the usual next step in the reductions) was not possible since the calibration frames (taken by an automated calibration sequence optimized for a different, long-term program at Mees) were not sufficiently exposed to be useful. Fortunately, the Thompson CCD used is intrinsically flat at ≤1% level. This was confirmed by our measured final S/N values which are typically ~130 in the continuum near the O I triplet. Even with this S/N the predicted 1σ uncertainty (Cayrel 1988) in our measured equivalent widths is ±0.6 mÅ. Measurements taken at the same position in different scans indicate the real value is ~1.2 mÅ, which is adequate for comparison with the measurements of Altrock (1968). Three (N–S) spatial elements were collapsed in the data cube to produce a final spectrum for each scan. The spectra we measure are taken from the same region of the data cube for consistency. No summing in the other spatial dimension was performed. Wavelength calibration was achieved using the O I triplet lines themselves and the Fe I line at 7780 Å.

2.2 *Results*

Two spectra at different disk positions are shown in Fig. 1. Equivalent widths of the O I lines were measured from two scans at each disk position in the IRAF package and averaged to yield the values listed in Table 1. Results are shown in Figs. 2(a)–2(c), which compare our results (filled symbols) with those of Altrock (1968; open symbols) for each triplet feature. The solid lines are LTE calculations for an O abundance of log ϵ(O)=8.91 (consistent with the ac-

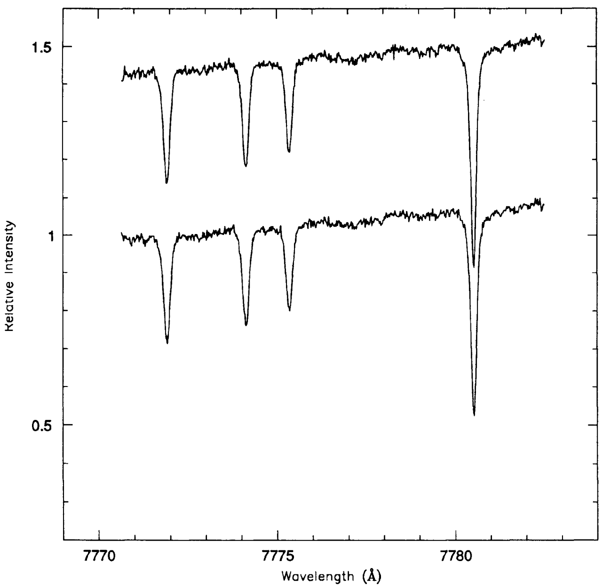

FIG. 1. Solar spectra of the 7774 Å region we acquired at Mees Solar Observatory. The spectra were taken at different values of μ and have been offset by an arbitrary constant for clarity. The O I lines at 7772, 7774, and 7775 Å are clear. The deep feature at 7781 Å is an Fe I line.

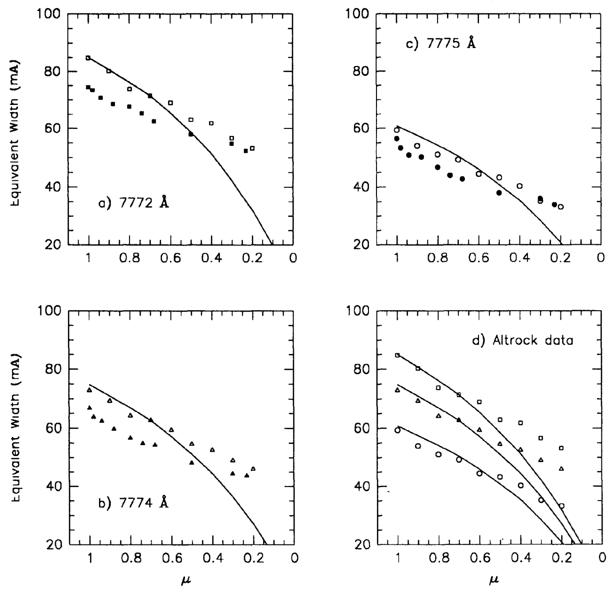

FIG. 2. (a) The equivalent width of the 7772 Å O I line as measured by Altrock (1968, open symbols) and us (filled symbols) is plotted against μ, the usual quantity which is equal to cos θ where theta is the apparent angle measured from disk center (θ=0°) to the limb (θ=90°). The solid line is the prediction from an LTE model calculation assuming an O abundance of 8.91. (b) Same as (a) except for the 7774 Å O I line. (c) Same as (a) except for the 7775 Å line. (d) The data of Altrock (1968) alone (symbols) for all three lines (from top to bottom: 7772, 7774, and 7775 Å) is plotted vs μ with our LTE model results for each line (solid lines).

cepted value of 8.93 and the recent determination of 8.86 by Biemont *et al.* 1991) using the Kurucz (1992) solar atmosphere. Figure 2(d) [analogous to Kiselman's (1991) Fig. 2] shows the data of Altrock (points) for each triplet feature vs our LTE model calculations (solid lines). Figure 3 compares Altrock's (1968) data points with NLTE calculations (described in TLLS) kindly provided by Drs. J. Tomkin and M. Lemke.

2.3 Discussion

Because our and Altrock's equivalent widths have typical uncertainties of ~1 mÅ, Figs. 2(a)–2(c) suggest that discrepancies exist between the two (particularly at large μ). A plausible explanation is that scattered light (perhaps increasing towards disk center) affects our data. This would decrease our equivalent widths relative to Altrock's as observed. We can check the scattered light using our disk center observations of the atmospheric *A* band near 7600 Å. The Kurucz *et al.* (1984, hereafter referred to as KFBT) atlas indicates the cores of the telluric lines reach the zero flux level. For our data, a very localized normalization makes the conservative (but poor) assumption that the peaks between the lines represent true continuum and, for this case, the *A*-band cores are ~6.7% above zero flux. A continuum level set just to the blue of the *A* band results in a value of 4.7%. The KFBT atlas continuum setting also yields a scattered light contribution of 4.7%. This level of contamination accounts for the discrepancy between our disk-center data and those of Altrock (1968); indeed, the top half of Table 2 indicates that

TABLE 1. Solar O I triplet equivalent widths.

μ (cos θ)	7772 Å (mÅ)	7774 Å (mÅ)	7775 Å (mÅ)
1.00	74.5	66.9	56.5
0.98	73.5	63.9	53.3
0.94	70.8	62.5	50.9
0.88	68.7	59.8	50.2
0.80	67.7	56.7	46.8
0.74	65.3	54.9	44.0
0.68	62.6	54.3	42.8
0.50	58.0	48.2	38.1
0.30	54.9	44.5	36.1
0.23	52.4	43.8	34.0

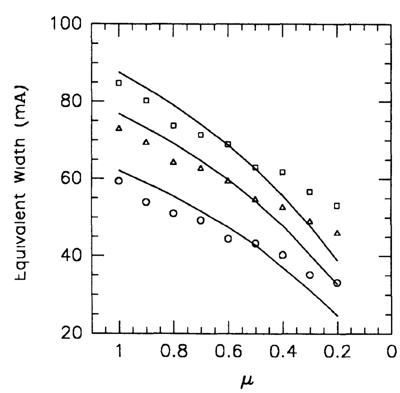

FIG. 3. The data of Altrock (1968, symbols) for each line in the O I triplet are plotted against μ. The solid lines are the predictions of a NLTE calculation by Tomkin *et al.* (1992).

TABLE 2. Comparison of solar 7774 Å O I equivalent widths.

Source	7772 Å (μ=1) (mÅ)	7774 Å (mÅ)	7775 Å (mÅ)	7772 Å (Integrated) (mÅ)	7774 Å (mÅ)	7775 Å (mÅ)
Altrock	84.8	72.9	59.4	-	-	-
JRK & AMB[a]	78.4	70.4	59.5	-	-	-
Utrecht Atlas	75	66	50	-	-	-
Liege Atlas	80.4	69.1	54.6	-	-	-
Edvardsson *et al.*	-	-	-	69.2	60.3	47.3
KFBT	-	-	-	77.1	66.6	52.0
AMB	-	-	-	71.5	62.0	45.7
JRK	-	-	-	72.0	59.0	45.3

[a]Corrected for 5.0% scattered light.

our corrected disk center values are consistent with those from other sources. We note that solar "surface" features (e.g., spots) were readily evident in our spatial–spatial and spatial–spectral data planes and avoided.

The main conclusions we draw from our data are the confirmation of Altrock's data (which we hold in high regard because of his use of a double-pass spectrograph) and the confirmation of the flatness of observed solar O I equivalent widths vs the LTE calculations at small μ. The difference between our data and the LTE calculations can be seen in Figs. 2(a)–2(c) and in Fig. 2(d) for Altrock's (1968) data. Kiselman's (1991) NLTE calculations match the equivalent width–μ morphology well, but his Fig. 2 indicates the NLTE equivalent widths are much too large. Figure 3 shows the NLTE calculations (solid lines) of TLLS, who included excitation effects due to collisions with neutral hydrogen, *versus* Altrock's (1968) data. Clearly, the agreement is much better though the disagreement with observations (confirmed here) still persists at small μ.

As a brief aside, we note that comparison of the flux measurements of Edvardsson *et al.* (1992) and AMB (Table 2) with the intensity measurements of Altrock (1968) and the LTE model calculations in Fig. 2, indicates the flux values are equivalent to the intensity measurements at μ=0.61–0.66. This is quite close to what one expects from the classical Eddington–Barbier relation (where the source function is a linear function of optical depth). We expect the Eddington–Barbier relation to hold in metal-poor stars too since the lines are weaker, lie on the linear portion of the curve of growth, and do not exhibit substantial wings (in opposite cases the source function is a higher order function of optical depth since the line profile outside the Doppler core may be a rapidly varying function of frequency or, for a strong line, there may be a large gradient [with height] in the Doppler width). However, conformity to the Eddington–Barbier relation says nothing about the validity of the LTE assumption. Rather, the point to be stressed is that LTE analyses of the 7774 Å O I *flux* measurements seem to yield the "correct" (judged by the abundances yielded by other O features) solar O abundance. Whether or not LTE analyses yield "correct" results for other stars depends on LTE departures and the extent of atmospheric inhomogeneities in these stars. In fact, we do not deny that the 7774 Å lines form in NLTE conditions even for the Sun (e.g., Altrock 1968). It also seems clear that inhomogeneities are present in the solar atmosphere as inferred from asymmetries in the O I triplet, noted by Altrock (1968) and Lambert (1978) and seen in our data, which vary as a function of μ. However, the issue at hand is whether the NLTE formation has a significant effect on abundances derived from *flux* spectra. Again, for the Sun this seems not to be the case since our 7774 Å abundance of log ϵ(O)=8.89 (see later) is perfectly consistent with the accepted value of 8.93.

3. 6300 AND 7774 Å O ABUNDANCES IN F AND G DWARFS

We now try to empirically determine what systematic effects are present in O abundance determinations by comparing the results from the 6300 Å [O I] line and the 7774 Å O I triplet for a selection of F and G dwarfs. We combine our own data taken for this purpose with data, which we reanalyze for homogeneity, from the literature.

3.1 The Data

Observations of the 6300 Å [O I] line and 7774 Å O I triplet in ten F field dwarfs were made by AMB using the 3.6 m CFHT during August and October 1987. The instrumentation consisted of the coudé spectrograph, red mirror train, a 830 1/mm grating, the *f*/8.2 camera, and a cooled 1872 Reticon detector (15 μm pixels). This configuration yielded a dispersion of 0.067 Å/pix while the measured resolution of the spectra was 0.11 Å. Comparison spectra were obtained each night for wavelength calibration. Multiple series of four flatfield exposures were performed nightly. Each set of four flatfields was iteratively summed and then each stellar spectrum was divided by the flatfield whose mean was within 10% of the stellar exposure level. A four-channel normalization was performed to remove pixel to pixel variations of the detector. The flattened spectra were then placed on a wavelength scale, continuum normalized, and divided by the spectra of the rapidly rotating B stars (observed at airmasses similar to the program objects and reduced in the same way) to remove telluric features. The S/N ratios of the final spectra are typically $\geqslant$400.

13 F and G dwarfs were observed by JRK on the nights of 1991 August 23–24 and 25–26 using the coudé spectrograph of the University of Hawaii 2.2 m telescope. The detector was a 1024×1024 Tektronix CCD and the measured resolution of the spectra was 0.16 Å. Exposure times ranged from

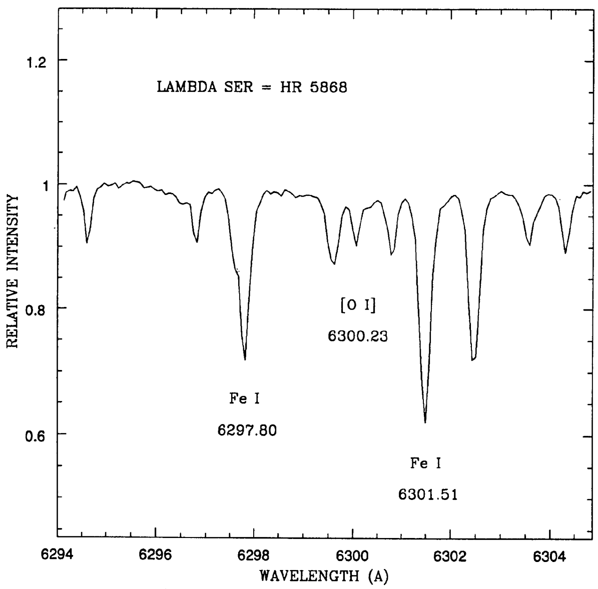

FIG. 4. A 6300 Å region spectrum of the star HR 5868 taken by AMB at CFHT. The [O I] line at 6300.3 Å is marked by the vertical line.

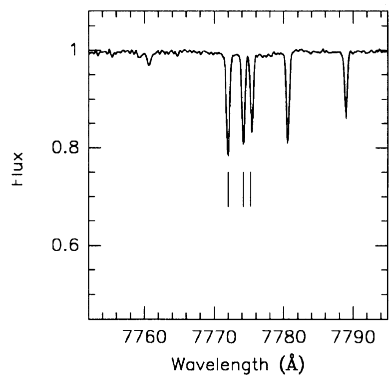

FIG. 5. A 7774 Å region spectrum of the star HR 8969 taken by JRK at the UH 2.2 m. The O I lines at 7772, 7774, and 7775 Å are marked by the vertical lines.

300 to 700 s for the 6300 Å observations and from 700 to 1200 s for the 7774 Å observations. The S/N of the reduced spectra is typically 300–400. Following standard reductions (trimming and removal of the detector dc offset), seven or eight flatfield frames were averaged (using 3σ clipping) to form a nightly flatfield frame which was then normalized with a low order cubic spline in the direction of dispersion. The bias-subtracted data were divided by the nightly flats to remove pixel-to-pixel variations. A moderate order cubic spline was fit in the dispersion direction some 10–20 pixels adjacent to (but well outside the wings) the spatial profile of the spectra in order to remove residual background (small dark current, sky background, bias levels slightly elevated above that in the overscan region, and extraneous light). The spectra were then traced, extracted, and wavelength calibrated (using 5–10 lines from Th–Ar lamp spectra) in IRAF. The wavelength calibrations used a low order Legendre polynomial and the rms residuals were ~0.005 Å. The spectra were then continuum normalized and (for the 6300 Å spectra) divided by spectra of rapidly rotating, hot stars to remove telluric lines.

Typical spectra of the 6300 and 7774 Å regions are shown in Figs. 4 and 5. We have supplemented our own data on 19 stars with that from the literature. NE92 have derived abundances for 23 F and G dwarfs from the permitted and forbidden lines. We reanalyze their data to ensure consistency with our own. We also utilize the data of Clegg *et al.* (1981, hereafter referred to as CLT). All stars in the combined sample are listed in the first column of Tables 3 and 4.

3.2 Stellar Parameters

3.2.1 [Fe/H]

We supplement iron abundances derived by AMB for a few of our stars with recent values from the literature—namely, the determinations of Edvardsson *et al.* (1993, hereafter referred to as EAGNLT93) and Balachandran (1990). These values are combined with other data from the literature (e.g., the catalog of Cayrel de Strobel *et al.* 1992) to determine the mean iron abundances given in column 6 of Table 3. The agreement between various sources is very good. We estimate a typical 1σ uncertainty of ±0.10 dex in our adopted values.

3.2.2 T_{eff}

We determined $T_{\rm eff}$ values for most stars using the Saxner & Hammarback (1985) relations. $(B-V)$ colors were taken from the Bright Star Catalog (Hoffleit & Jaschek 1982) or the SIMBAD database. Strongren indices $[(b-y)$ and H$\beta]$, were taken from Hauck & Mermilliod (1990). The final temperatures are listed in column two of Table 3. Uncertainties, based on the variance of the determinations from each photometric index, are listed in column three. For the five most metal-poor stars studied by NE92, temperatures were derived using the $(b-y)-T_{\rm eff}$ relation given in King (1993); the resulting values are only slightly larger than those adopted by NE92. The photometric indices of HR 7462 lie outside the range of the Saxner & Hammarback (1985) calibrations. We derived the $T_{\rm eff}$ for this star by mating the theoretical $(B-V)-$ and $(b-y)-T_{\rm eff}$ relations of the new Kurucz (1992) models to the Saxner & Hammarback (1985) relations at $(B-V)$=0.63. For 38 stars in common with EAGNLT93, the mean difference (our temperatures minus those of EAGNLT93) is -36.2 ± 38.5 K. There is a clear trend (the correlation coefficient indicates the significance is at the 99.5% confidence level) in the sense that we derive smaller $T_{\rm eff}$ values for hotter stars. A more rigorous parameter determination might adjust the adopted metal abundances based on the adopted $T_{\rm eff}$. This modified [Fe/H] value would then be used to recalculate $T_{\rm eff}$ and the process iterated. In our case, however, the changes are extremely small and well within the estimated uncertainties. We therefore retain the initially estimated [Fe/H] and $T_{\rm eff}$ values.

TABLE 3. Stellar parameters.

Star	$T_{\rm eff}$ (K)	$\sigma(T_{\rm eff})$ (K)	log g	σ(log g)	[Fe/H]	ξ (km/s)
HR 33	6156	45	4.12	0.16	−0.40	1.85
HR 219	5900	80	4.41	0.16	−0.27	1.30
HR 483	5883	30	4.25	0.16	+0.02	1.48
HR 573	6176	78	4.28	0.16	−0.34	1.70
HR 781	6409	23	4.22	0.15	−0.21	1.95
HR 870	6454	45	4.10	0.15	+0.20	2.15
HR 996	5673	79	4.27	0.21	+0.03	1.30
HR 1010	5821	57	4.33	0.17	−0.21	1.35
HR 1101	5983	32	4.16	0.15	−0.10	1.70
HR 1294	5745	57	4.17	0.15	−0.18	1.50
HR 1536	5926	66	3.99	0.15	+0.14	1.85
HR 1673	6386	53	4.10	0.17	−0.30	2.10
HR 1729	5852	32	4.11	0.15	+0.03	1.65
HR 2354	5787	87	4.11	0.16	+0.13	1.60
HR 2493	6010	52	4.25	0.15	−0.37	1.60
HR 2548	6369	32	4.12	0.15	−0.20	2.05
HR 2883	5905	46	4.18	0.15	−0.77	1.60
HR 2943	6585	26	4.07	0.16	−0.02	2.30
HR 3018	5806	25	4.38	0.17	−0.84	1.25
HR 3775	6344	30	4.11	0.15	−0.15	2.05
HR 4529	6074	45	4.04	0.15	+0.16	1.90
HR 4533	6304	24	4.18	0.15	+0.20	1.90
HR 4540	6149	20	4.16	0.16	+0.13	1.80
HR 4734	5710	41	4.17	0.18	+0.10	1.45
HR 4903	5915	46	4.00	0.17	+0.24	1.80
HR 4983	6009	41	4.31	0.17	+0.06	1.50
HR 5868	5915	27	4.18	0.16	−0.03	1.60
HR 5933	6276	42	4.25	0.15	−0.14	1.80
HR 6212	5754	79	3.95	0.15	+0.07	1.75
HR 6467	6405	7	4.20	0.16	−0.42	1.95
HR 6541	6228	42	3.96	0.16	−0.21	2.10
HR 7322	6313	81	4.16	0.15	−0.28	1.95
HR 7462	5237	47	4.65	0.35	−0.24	0.80
HR 7503	5790	77	4.10	0.15	+0.08	1.60
HR 7504	5719	63	4.09	0.16	+0.03	1.55
HR 7534	6345	45	4.22	0.15	−0.13	1.90
HR 7672	5880	85	4.34	0.19	−0.11	1.35
HR 8077	6116	16	4.08	0.16	−0.09	1.90
HR 8181	6134	67	4.35	0.16	−0.71	1.55
HR 8314	5926	69	4.30	0.15	+0.03	1.45
HR 8805	6469	32	4.21	0.15	−0.14	2.00
HR 8825	6366	69	4.15	0.16	−0.20	2.00
HR 8969	6157	49	4.17	0.15	−0.21	1.80
HD 22879	5859	74	4.29	0.15	−0.84	1.40
HD 51929	5853	70	4.26	0.15	−0.72	1.45
HD 78558	5707	31	4.23	0.17	−0.40	1.35
HD 89707	5966	34	4.42	0.15	−0.42	1.35
HD 98553	5898	59	4.36	0.15	−0.43	1.35
HD 130551	6251	34	4.26	0.15	−0.62	1.72
Sun	5770	15	4.44	0.1	+0.00	1.15

3.2.3 Log g and ξ

The stellar gravities were determined in two ways. First, when available, we took EAGNLT93's estimates, which are based on a Stromgren photometric calibration. Second, we estimated the gravities based on the $(b-y)$ and c_1 indices of the new Kurucz (1992) models by comparing loci of constant gravity in the c_1 *versus* $(b-y)$ plane. The difference between the two determinations (EAGNLT93 minus Kurucz) is plotted against the Kurucz model log g value in Fig. 6, which shows a clear trend. The Kurucz model values were placed on the EAGNLT93 scale (which we feel has greater external accuracy) via the relation shown by the solid line in Fig. 6:

$$\Delta \log g = -0.662 \log g(\text{Kurucz}) + 2.908.$$

Transformed Kurucz values were averaged with the EAGNLT93 values to produce the values listed in column four of Table 3. Gravities from the literature were also used for the purpose of estimating uncertainties, which are shown in column five. Finally, microturbulent velocities come from

TABLE 4. Equivalent widths and abundances.

Star	EW(6300) mÅ	σ mÅ	Ref.	EW(7774) mÅ	σ mÅ	Ref	log ϵ(O) 6300Å	σ dex	log ϵ(O) 7774Å	σ dex
HR 33	5.9	1.8	JRK	242.2	7	JRK	8.76	0.18	8.61	0.07
HR 219	4.4	0.5	CLT	185.0	13	CLT	8.74	0.09	8.77	0.11
	4.6	-	SLW	178.0	-	SLW	-	-	-	-
HR 483	6.2	0.8	CLT	192.2	20	CLT	8.93	0.07	8.76	0.12
	6.8	1.2	JRK	213.8	7	JRK	-	-	-	-
HR 573	3.55	0.15	NE	-	-	NE	8.60	0.08	8.63	-
HR 781	6.5	2.5	JRK	341.0	8	JRK	8.94	0.24	8.97	0.05
HR 870	9.2	2.8	JRK	442.8	7	JRK	9.20	0.13	9.28	0.06
HR 996	7.4	1.7	JRK	174.5	6	JRK	8.97	0.15	8.88	0.11
HR 1010	3.45	0.6	NE	-	-	NE	8.62	0.12	8.65	-
HR 1101	5.25	0.5	NE	-	-	NE	8.81	0.08	8.90	-
HR 1294	5.1	0.4	NE	-	-	NE	8.74	0.08	8.72	-
HR 1536	7.55	0.75	NE	-	-	NE	8.97	0.08	8.91	-
HR 1673	4.6	0.5	GO	320.0	14	CLT	8.72	0.11	8.86	0.08
HR 1729	7.6	0.8	CLT	219.0	14	CLT	8.97	0.09	8.87	0.10
	-	-	-	228.0	-	SLW	-	-	-	-
HR 2354	7.85	0.45	NE	-	-	NE	8.97	0.07	8.94	-
HR 2493	3.65	0.35	NE	-	-	NE	8.55	0.09	8.52	-
HR 2548	3.5	0.1	NE	-	-	-	8.63	0.06	-	-
HR 2883	3.9	0.4	NE	-	-	NE	8.46	0.08	8.56	-
HR 2943	3.7	0.3	NE	-	-	NE	8.74	0.08	9.07	-
HR 3018	3.35	0.15	NE	-	-	NE	8.42	0.07	8.62	-
HR 3775	4.7	0.5	CLT	342.0	18	CLT	8.76	0.08	8.96	0.08
HR 4529	9.5	0.2	NE	-	-	-	9.13	0.07	-	-
HR 4533	6.85	0.15	NE	-	-	-	9.08	0.06	-	-
HR 4540	6.6	0.7	CLT	309.0	12	CLT	9.01	0.08	9.05	0.07
	6.4	0.2	NE	-	-	NE	9.01	0.06	8.96	
HR 4734	8.37	0.85	NE	-	-	NE	9.00	0.09	8.90	-
HR 4903	10.85	0.15	NE	-	-	NE	9.13	0.07	9.16	-
HR 4983	5.7	0.6	CLT	229.0	10	CLT	8.97	0.08	8.86	0.07
HR 5868	8.5	0.8	AMB	226.4	12	AMB	9.06	0.05	8.88	0.08
HR 5933	6.0	0.9	CLT	275.0	15	CLT	8.92	0.10	8.81	0.08
HR 6212	12.4	1.2	AMB	272.0	13	AMB	9.09	0.08	9.15	0.09
HR 6467	2.7	0.5	AMB	298.3	10	AMB	8.51	0.10	8.79	0.06
	2.7	0.8	JRK	304.6	7	JRK	-	-	-	-
HR 6541	6.0	0.6	AMB	332.0	17	AMB	8.76	0.07	8.97	0.09
HR 7322	6.3	0.6	AMB	319.3	16	AMB	8.86	0.08	8.94	0.10
HR 7462	3.6	0.6	CLT	69.0	4	CLT	8.62	0.16	8.68	0.13
HR 7503	5.4	0.5	AMB	209.8	7	AMB	8.79	0.08	8.87	0.09
	5.8	0.9	JRK	197.8	4	JRK	-	-	-	-
HR 7504	6.7	0.6	AMB	186.9	10	AMB	8.87	0.08	8.82	0.10
	6.8	1.1	JRK	-	-	-	-	-	-	-
HR 7534	4.1	1.6	JRK	324.5	7	JRK	8.77	0.23	8.95	0.05
HR 7672	6.8	1.3	JRK	219.4	6	JRK	8.97	0.15	8.90	0.08
HR 8077	8.5	1.0	JRK	313.8	5	JRK	9.01	0.09	9.03	0.04
HR 8181	3.0	0.6	BE	-	-	E93	8.49	0.13	8.39	-
HR 8314	5.7	0.8	AMB	220.1	11	AMB	8.92	0.10	8.89	0.09
HR 8805	4.3	1.1	JRK	379.0	9	JRK	8.80	0.23	9.08	0.06
HR 8825	2.7	0.4	AMB	343.7	25	AMB	8.53	0.10	8.99	0.12
HR 8969	6.2	0.6	AMB	290.7	10	AMB	8.85	0.09	8.96	0.05
	-	-	-	284.3	4	JRK	-	-	-	-
HD 22879	2.9	0.3	NE	-	-	NE	8.34	0.08	8.51	-
HD 51929	3.95	0.1	NE	-	-	NE	8.49	0.07	8.61	-
HD 78558	6.5	0.3	NE	-	-	NE	8.78	0.06	8.86	-
HD 89707	3.3	0.5	NE	-	-	NE	8.56	0.10	8.61	-
HD 98553	3.1	0.3	NE	-	-	NE	8.51	0.08	8.44	-
HD 130551	2.8	0.5	NE	-	-	NE	8.47	0.11	8.53	-
Sun	5.94	0.3	K84	179.2	4	AMB	8.95	0.02	8.89	0.02

References. — (1) AMB, CFHT data this paper (2) BE, Barbuy & Erdelyi-Mendes (1989) (3) CLT, Clegg et al. 1981 (4) E93=EAGNLT93, Edvardsson et al. (1993) (5) GO, Gratton & Ortolani (1986) (6) JRK, UH 2.2-m data this paper (7) K84, Kurucz et al. (1984) atlas (8) NE92, Nissen & Edvardsson (1992)

the empirically derived relation of EAGNLT93 [their Eq. (9)], which is similar to that found by Nissen (1981). The values are listed in the final column of Table 3 and are nearly identical to those used by EAGNLT93.

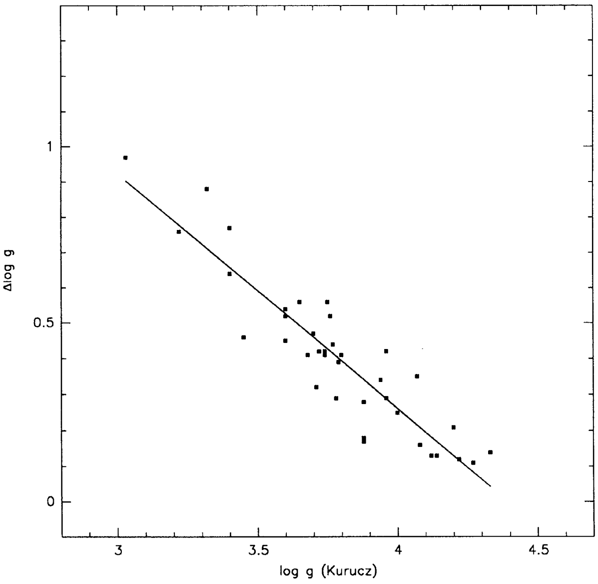

FIG. 6. The difference in the log g values of EAGNLT93 and those predicted from Stromgren colors of the new Kurucz (1992) models are plotted against the Kurucz model values. The solid line is an ordinary least squares regression to the data points and is used to place the Kurucz model values on the scale of EAGNLT93.

4. ABUNDANCE ANALYSIS AND AN EXAMINATION OF UNCERTAINTIES

4.1 *Equivalent Widths*

The IRAF and DOUBLEPLAY packages were used to measure equivalent widths. Table 4 lists the 6300 Å equivalent width, estimated uncertainty, and source in columns 2, 3, and 4. Columns 5, 6, and 7 give the *whole* 7774 Å equivalent width (though the three lines were measured individually), uncertainty, and source. NE92 do not provide 7774 Å equivalent widths so no values are given; we describe later how 7774 Å O abundances for these stars were determined. For the literature data, we assigned reasonable uncertainties based on resolution and S/N. In order to ensure some homogeneity, only one source was used to derive O abundances for a star with multiple data sources.. We preferred the 6300 Å measurements of AMB and CLT over those of JRK, due to the latter's lower resolution. The same source was used for both the 6300 and 7774 Å measurements. Multiple abundance estimates are made for HR 4540 since this permits comparison between our determination from the CLT data and our indirect reanalysis of the NE92 data. The determinations are treated as independent data points. Comparison of common data indicates very good agreement between the 6300 and 7774 Å equivalent widths of AMB, JRK, and CLT.

The bottom half of Table 2 presents various flux-based estimates of the solar 7774 Å equivalent widths. The values measured by NE92, EAGNLT93, AMB, and JRK from independent data sources are in good agreement. The KFBT atlas value, however, is larger than these other measurements. The solar forbidden line equivalent width is also somewhat uncertain. Lambert (1978) adopted 4.55 mÅ for the solar equivalent width (N.B. this is a disk center value). NE92 adopt a value of 5.3 mÅ based on the KFBT atlas, though they measure a value of 5.7 mÅ from their own spectrograms. We also measured the equivalent width from the KFBT atlas. Adopting a pseudocontinuum just above apparent continuum "windows" yielded 5.4 mÅ. A continuum setting consistent with our stellar one resulted in 5.9 mÅ. Using the continuum normalization of the KFBT atlas itself, however, results in ~7.9 mÅ.

These comparisons suggest the solar equivalent width may be a source of systematic differences in stellar [O/H] ratios. Therefore, the Sun is considered as an individual data point to perform the normalization of the stellar O abundances. Our solar 7774 Å measurement is from a moderately high resolution (0.21 Å) spectrum, acquired by AMB, of the asteroid Vesta. We set the continuum in a manner consistent with the stellar spectra. Our solar 6300 Å measurement is from the KFBT atlas, renormalized so that the continuum placement is consistent with the stellar data. Happily, this value is in very good agreement with measurements of daytime sky spectra acquired at the 2.7 m McDonald Observatory with the 2Dcoude system in January 1994 by JRK. Our solar equivalent widths and estimated uncertainties are given in Table 4. Normalization to a solar abundance derived in fashion consistent with the stellar abundances for each line makes the resulting [O/H] values independent of the adopted gf values and (to first order) the adopted continuum normalization.

4.2 Atomic Parameters

For the 6300 Å [O I] line, we adopted an oscillator strength of $\log gf=-9.75$ (Lambert 1978), a relatively well determined value also used by NE92. For the 7772, 7774, and 7775 Å O I lines, we adopted $\log gf=+0.333$, $+0.186$, and -0.035 (Wiese *et al.* 1966). The $\log gf$ values used by NE92 (kindly communicated by Dr. P. Nissen) are smaller by ~0.105 dex. NE92's study is based on a portion of the data presented in full by EAGNLT93, who determined $\log gf$ values from an assumed solar O abundance of 8.93 and their equivalent widths of the individual 7774 Å triplet lines totaling 176.8 mÅ (compared with the 175.8 mÅ used by NE92). The EAGNLT93 $\log gf$ values are 0.03 dex *larger* than those of NE92 despite the fact that a *larger* solar O abundance (8.93 vs 8.90) was assumed by EAGNLT93—opposite to expectation. Dr. P. Nissen has informed us that their continuous opacity code was updated between the NE92 and EAGNLT93 analyses; this may be the cause of the minor discrepancy. Finally, Biemont *et al.* (1991) derived larger oscillator strengths than what we use. They find $\log gf=+0.35$, $+0.21$, and -0.02 from their configuration interaction code and $\log gf=+0.40$, $+0.25$, and $+0.03$ from their Hartree–Fock calculations.

Thus, there is a disturbing 0.17 dex range in the 7774 Å $\log gf$ values used in recent analyses. That some genuine discrepancy exists can be illustrated as follows. Our total 7774 Å equivalent width is 179.2 mÅ while NE92 use a value of 175.8 mÅ. Both we and NE92 would use essentially the same equivalent width and solar O abundance (we find 8.89 while they assume 8.90) and yet (when inverting the problem to determine oscillator strengths) we would determine $\log gf$ values differing by 0.10–0.11 dex. We believe that most of this discrepancy can be explained by our differences in the treatment of line broadening (see below). However, the slight remaining differences could be due to use of different model atmospheres; NE92 employed new, updated Gustafsson (Gustafsson *et al.* 1975) atmospheres while ours were from the new grids of Kurucz (1992).

We use a radiative damping constant of 1.3×10^{8} s^{-1}. Classical van der Waals damping was calculated according to the formulation of Unsold (1955), using the expression for C_6 from Gray (1992) with an enhancement factor of ~1.2. EAGNLT93 use different values/enhancements for these parameters and we assume that this was also done in NE92. Garcia Lopez *et al.* (1993) use an enhancement factor of 6 in their recent 7774 Å O I analysis. They indicate that this enhancement will lower the derived O abundance by 0.16 dex compared to the no enhancement case. Although this is a large amount, consistent application to consistent solar and stellar data prevents the enhancement factor from affecting the normalized O abundances.

Constructing curves of growth for the solar case using the EAGNLT93 constants, we find an abundance difference of 0.085 dex. Thus, this amount of the $\log gf$ value discrepancy might be explained by the differing treatment of line broadening. This would leave a ~0.02 dex discrepancy, which we think represents entirely satisfactory agreement given other possible uncertainties. Still, if is to be claimed (as did EAGNLT93) that systematic uncertainties in elemental abundance ratios ([X/Fe]) are only 0.05–0.10 dex, then even small discrepancies deserve to be scrutinized. Specifically, we have seen that systematic differences of 0.06 dex might be attributed to differences in the treatment of continuum opacity. The 0.02 dex $\log gf$ difference could be attributed to differences in model atmospheres. Thus, the potential systematic uncertainties in the O abundance alone (i.e., not even considering effects on the Fe abundance–a necessary consideration in evaluating [X/Fe]) seem to already be approaching the level noted by EAGNLT93. When one also considers possible systematic effects due to $T_{\rm eff}$ scale, equivalent widths, values of microturbulence, $\log g$ scale, and NLTE, the differences might become even larger. Thus, for the specific ratio [O/Fe], the claim of EAGNLT93 that systematic differences are only 0.05–0.10 dex may be an optimistic one; even closer examination of all relevant parameters is necessary to tell for sure.

Acting on the suggestion of the referee, we attempted to analyze other high excitation features in the solar spectrum. In limiting ourselves to transitions observed with the same instrumentation used here (to minimize systematic uncertainties) and having laboratory or theoretical oscillator strengths, we were left with the seven high excitation (8.6 eV) C I features (six between 7100 and 7120 Å) discussed by Friel & Boesgaard (1990). The equivalent widths from their high S/N, resolution CFHT sky spectra were taken from their Table 2(i). The abundances were derived via LTE curves of growth using the Kurucz (1992) solar model atmosphere and the theoretical $\log gf$ values kindly provided by Dr. J. Tomkin based on the calculations of Hibbert *et al.* (1993). For the 6587 Å feature, we used the theoretical $\log gf$ value of -1.34 from Wiese *et al.* (1966).

Discarding the highly discrepant result from the 7100 Å line, the mean logarithmic abundance so derived was $\log \epsilon(\mathrm{C})=8.60\pm0.07$ (retaining the line results in a value of 8.66), where the uncertainty is the error of the mean. This value is in exact agreement with the "final recommended solar abundance" of 8.60 derived by Grevesse *et al.* (1991). More recent values are somewhat lower (~8.56; e.g., Grevesse & Anders 1989). Based on these results, we have no reason to believe that our choice of model atmospheres introduces significant discrepancies into the abundances from high excitation lines. Even if the face value difference of 0.05–0.10 dex between our derived value and the preferred solar abundance is genuine, it would suggest a need to *raise* our $\log gf$ values—this is in opposite sense to that noted above, where we would need to *lower* our O I gf values to bring them into agreement with the EAGNLT93/NE92 values.

4.3 The O Abundances

O abundances were determined from measured equivalent widths using curves of growth constructed with the LTE analysis software RAI10 (courtesy Dr. M. Spite) and model atmospheres from the extensive grid of Kurucz (1992). Given the large number of curves of growth constructed, it was an easy matter to interpolate among them (using low order polynomials) to determine abundances for a given equivalent width and set of stellar parameters.

4.3.1 6300 Å [O I] abundances

Our 6300 Å abundances, $\log \epsilon(\mathrm{O})$ on the usual logarithmic scale with $\log \epsilon(\mathrm{H})=12.0$, and uncertainties are listed in columns eight and nine of Table 4. Uncertainties were determined by adding the contributions due to errors in the equivalent width, $T_{\rm eff}$, $\log g$, and [Fe/H] in quadrature. The mean difference (KB94−NE92) of NE92's absolute O abundances (*not* [O/H]) and those in our reanalysis is -0.010 ± 0.047 (1σ) dex—precisely that expected from the slightly lower $T_{\rm eff}$ values we adopt (changing the adopted $T_{\rm eff}$ by ± 100 K typically changes the derived 6300 Å O abundance by ± 0.03 dex for our stars). The excellent agreement indicates that the different software and model atmospheres do not significantly affect the absolute 6300 Å abundances.

4.3.2 7774 Å O I abundances

Since 7774 Å equivalent widths were not presented in NE92, we "rederive" abundances as follows. NE92's absolute 7774 Å abundances were found from columns six and two of their Table 4 and their assumed solar abundance of 8.90. Using our adopted parameters, we constructed curves of growth and adjusted NE92's absolute abundances by examining the sensitivity to $T_{\rm eff}$, $\log g$, [Fe/H], and ξ. The revised absolute abundances were reduced by 0.105 dex for consistency with our $\log gf$ values. Abundances for our own data were determined directly from the equivalent widths using curves of growth just as for the 6300 Å data. Final 7774 Å abundances and uncertainties for all stars are given in columns 10 and 11 of Table 4. The only 7774 Å data for HR 8181, whose 6300 Å data is not from one of the four main sources used, are those of EAGNLT93. This star's O abundance was rederived using the same procedure as for the NE92 data except that we first converted the "corrected" O abundance of EAGNLT93 to a 7774 Å abundance using their Eq. (11).

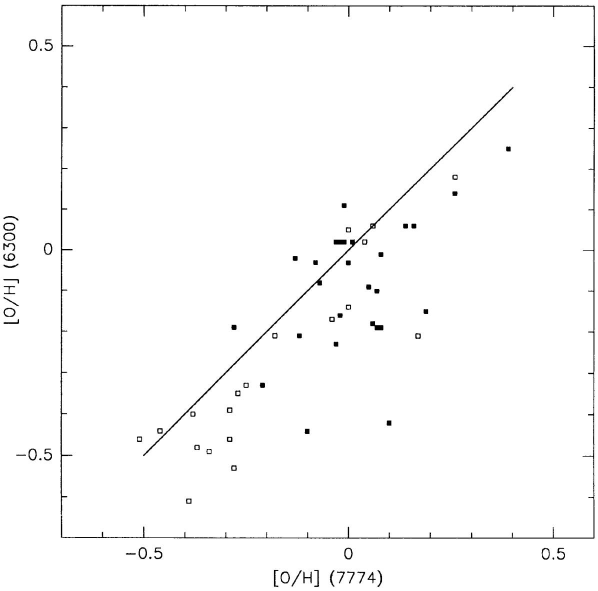

FIG. 7. The [O/H] ratio as derived from the 6300 Å [O I] line is plotted against the [O/H] ratio derived from the 7774 Å O I lines. The open squares are the reanalyzed data of NE92. The filled squares represent all other data used here. The solid line is the one-to-one relation expected if the two [O/H] ratios are equal. It can be seen that the 7774 Å O I lines appear to yield larger O abundances.

The mean difference (KB94−NE92) between NE92's *absolute* 7774 Å abundances and our reanalyzed values is -0.093 ± 0.033 (1σ) dex. No adjustment of the abundances for our choice of $\log gf$ results in a mean difference of $\sim +0.012$ dex, nearly that expected from our slightly lower (on average) $T_{\rm eff}$ values (changing the adopted $T_{\rm eff}$ by ± 100 K typically changes the derived 7774 Å O abundance by ∓ 0.10 dex for our stars). We also note that our 7774 Å abundances were derived from the sum of the triplet lines' equivalent widths. Averaging results from the individual lines did not yield different abundances. Indeed, Boesgaard & King (1993) found the O abundances derived from the individual triplet lines in very good agreement and the average of these values is not significantly different than the value derived from the sum total of the triplet lines. This result has been reconfirmed by AMB, who derived abundances for the stars observed for this paper from the individual lines and found them to be in excellent agreement.

5. RESULTS AND DISCUSSION

5.1 [O/H] (6300 Å) vs [O/H] (7774 Å)

We take the final absolute O abundances and normalize them to the appropriate (6300 or 7774 Å) solar abundance given in Table 4. The relative 6300 Å [O I] abundances are plotted against the 7774 Å O I abundances in Fig. 7. Open squares are NE92 sample data and filled squares are all other data. The solid line is the equal abundance relation. Figure 7

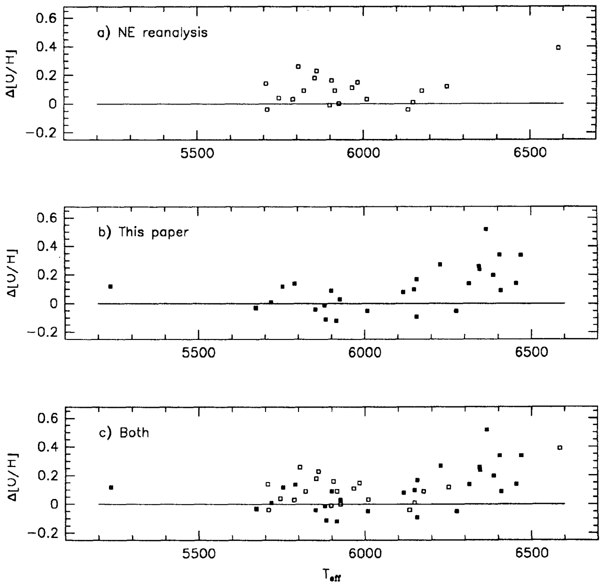

FIG. 8. (a) Δ[O/H], defined as [O/H] (7774 Å)$-$[O/H](6300 Å), is plotted against our effective temperature for the stars of NE92 which are reanalyzed here. (b) Same as (a) except showing all the data in Table 4 other than NE92's. An increase in Δ[O/H] for $T_{\rm eff}\gtrsim 6200$ K is seen. (c) The data in (a) and (b) are plotted together.

suggests [O/H] ratios determined from the 7774 Å triplet are larger than those from the 6300 Å line. However, the majority of "misfits" are high $T_{\rm eff}$ stars (see below).

5.1.1 Δ[O/H] vs T_{eff}

The quantity Δ[O/H]=[O/H](7774)$-$[O/H](6300) is calculated and plotted *versus* $T_{\rm eff}$ in Figs. 8(a)–8(c) for the reanalyzed data of NE92, all other data, and both samples. For $T_{\rm eff}\gtrsim 6200-6300$ K, Fig. 8(c) clearly shows a large increase in Δ[O/H]—a result expected from known NLTE effects on 7774 Å abundances in early-type stars (e.g., Bascheck *et al.* 1977). It seems clear we are seeing the onset of these NLTE effects.

Figures 8(a) and 8(b) reveal conflicting results. For $T_{\rm eff}\lesssim 6200$ K, the reanalyzed NE92 stars have a mean Δ[O/H] of $+0.092\pm0.086$ (1σ) dex. The rest of our sample having $T_{\rm eff}\lesssim 6200$ K has a mean Δ[O/H] of 0.026 ± 0.094 dex. The result for the NE92 stars is not introduced by our reanalysis as shown in Fig. 9, which plots the original data of NE92 unadjusted in manner. Here, the mean Δ[O/H] for $T_{\rm eff}\lesssim 6200$ K is $+0.117\pm0.094$. While NE92's results suggested systematic differences between 6300 and 7774 Å O abundances of their relatively metal-rich sample stars, our data [shown in Fig. 8(b)] are not consistent with this conclusion for $T_{\rm eff}\lesssim 6200$ K. No significant differences between the [O I] and O I abundances are apparent in our data (or that of Clegg *et al.* 1981). Our different result is not due to different parameter values since the slightly lower (on average) $T_{\rm eff}$ estimates we employ should yield slightly larger O I and slightly lower [O I] abundances, resulting in our Δ[O/H] values being larger *ceteris paribus*.

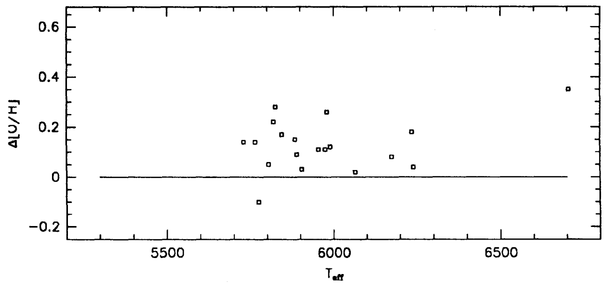

FIG. 9. Same as Fig. 8(a) except the original abundances and $T_{\rm eff}$ values of NE92 are used. The significantly positive value of Δ[O/H] seen in Fig. 8(a) persists.

5.1.2 Δ[O/H] vs [Fe/H]

NE92 find the difference between the [O I] and O I abundances to increase with decreasing [Fe/H]. This is consistent with Kiselman's (1991) NLTE calculations, but could also be due to inadequacies in model atmospheres (e.g., inhomogeneity effects) increasing at lower metallicities. As shown in Fig. 10(a), the increasing difference persists in the reanalyzed NE92 data having $T_{\rm eff}<6200$ K and the correlation coefficient indicates the trend is significant at the 98.8% confidence level. While Fig. 10(b) shows no obvious trend (the statistical significance is at <50% confidence level) in the non-NE92 data having $T_{\rm eff}<6200$ K, the data do not reach metallicities as low as the NE92 data. The calculations of Takeda (1994) indicate that NLTE effects *decrease* with decreasing metallicity (consistent with TLLS' NLTE calcula-

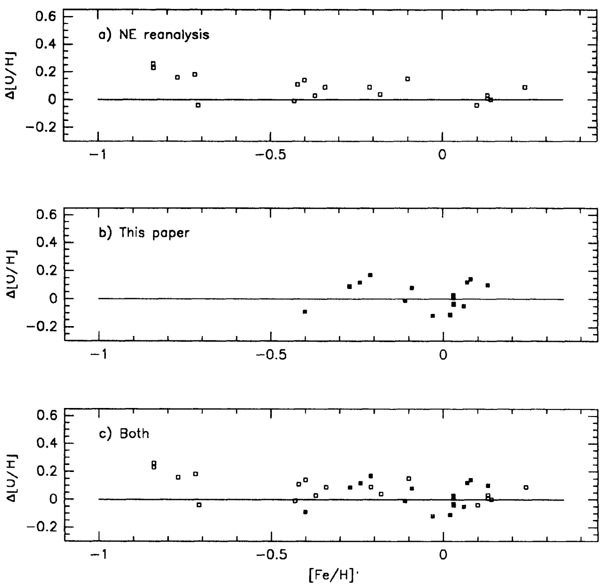

FIG. 10. (a) Δ[O/H] is plotted vs [Fe/H] for the reanalyzed NE92 data. A significant trend of increasing Δ[O/H] with declining [Fe/H] is seen. (b) Same as (a) except showing all the data in Table 4 other than NE92's. No trend with declining [Fe/H] is seen, but the range of [Fe/H] is limited. (c) The data in (a) and (b) are plotted together.

tions). Unfortunately, our data does little to resolve the issue. For completeness, Fig. 10(c) shows Figs. 10(a) and 10(b) plotted together.

5.2 *Is There a 7774–6300 Å Discrepancy?*

Our own data as well as that of Clegg *et al.* (1981) suggests that, within the errors, there is no significant difference between the [O I] and O I abundances for $T_{\rm eff} \lesssim 6200-6300$ K. While we cannot explain the conflict with NE92's results, the difference seems to rest in the 7774 Å abundances. The most likely explanations are differences in the model atmospheres, analysis software, or the data themselves. The only independent evidence of possible deficiencies in either analysis that we are aware of is the increasing difference in Δ[O/H] with decreasing [Fe/H] found by NE92, a result which conflicts with the Takeda's (1994) NLTE calculations, which predict decreasing Δ[O/H] with decreasing [Fe/H] (again, consistent with the NLTE calculations of TLLS).

An explanation of this discrepancy (noted by NE92) is that NE92's increasing Δ[O/H] with declining [Fe/H] is due to the effects of inhomogeneities and not NLTE. Empirical evidence seems to argue against this. The [O/Fe] ratios determined from the *forbidden* line by Spite & Spite (1991) for HD 103095 and HD 132475 (the two most metal-poor stars in their sample) are in excellent agreement with the mean ratio determined from the *permitted* lines for several halo dwarfs by King (1993) in his reanalysis of TLLS' data. This agreement exists whether or not one applies King's advocated $T_{\rm eff}$ and metallicity scale to the Spite & Spite (1991) results. Additionally, King's (1993) mean [O/Fe] ratio agrees closely with those of metal-poor giants as determined from the *forbidden* line (King 1994).

While the empirical evidence does not exclude small (~0.05 dex or so) differences between the forbidden- and permitted-line O abundances in metal-poor stars, it may not support NE92's suggestion. Although the definitive explanation of this discrepancy is not evident, the effects of atmospheric inhomogeneities on O abundances should still be vigorously investigated using hydrodynamical calculations like those of Nordlund & Dravins (1990). As the referee has pointed out, such calculations might require inclusion of even further unconsidered physics to fully understand the effects of stellar atmospheric processes on abundance determinations. For some stars, a chromospheric thermal bifurcation, the effects of chromospheric back heating, and the presence of a cool COmosphere (Ayres 1994) might have an impact on derived photospheric O abundances. Detailed calculations including these phenomena are needed to gauge their importance and magnitude.

5.3 *Reliability of 6300 Å Abundances?*

The 6300 Å [O I] O abundances have usually been assumed to be more reliable than those from the 7774 Å triplet. The discrepancies noted in previous sections do reinforce the notion of moderately large systematic uncertainties for the 7774 Å abundances, but several recent results indicate that comparable uncertainties may exist for the 6300 Å values. In particular, the pseudo-two-stream calculations of TLLS indicate that, in the case of hot and cold streams each 400 K different than the actual stellar $T_{\rm eff}$, the 7774 Å O I abundance would be reduced by 0.09 dex for HD 103095. Their derived 6300 Å [O I] abundance would, however, *increase* by 0.16 dex. Without further detailed calculations, we can only state that the belief that atmospheric inhomogeneities adversely affect the permitted lines' usefulness might also apply to the forbidden line.

Comparing results of recent analyses also indicates the 6300 Å abundances' reliability may be in question. Francois *et al.* (1988) derived [O/Fe]~+0.36 for the giant star No. 74 in ω Cen. Using the same data, Milone *et al.* (1992) derive [O/Fe]=+0.20. Because the derived O abundance from the [O I] line is insensitive to model atmosphere variations, this difference seems surprisingly large since the adopted parameters were the same (as was the Fe abundance). Furthermore, Brown & Wallerstein (1993) analyze their own data and determine [O/Fe]=+0.55. This ratio is in good accord with Brown *et al.* (1991a), who found [O/Fe]=+0.49 from similar, but distinct, data. Since the adopted $T_{\rm eff}$ of Brown and collaborators differs by only 15 K from the other two analyses, the discrepancy is worrisome. We also cite the case of the M13 red giant I-48, whose [O/Fe] ratio derived from forbidden lines by Brown *et al.* (1991b) differs by 0.5 dex, 0.22 dex of which is due to O abundance, from that found by Kraft *et al.* (1993). The latter also reobserved and reanalyzed three stars from Kraft *et al.* (1992). δ[Fe/H] and δ[O/Fe] in the Appendix of Kraft *et al.* (1993) indicate that the average [O/H] determination (from forbidden lines) differed by 0.17 dex. Finally, we note the inability of Bessell *et al.* (1991) to reproduce many of the red giant forbidden line abundances of others. The situation for forbidden-line abundances of dwarfs may be more troubling: the equivalent widths for the giants noted above range from ~15 to ~40 mÅ while the dwarfs have much weaker lines (e.g., ~5 Å for the Sun). Thus, measurement uncertainties may be larger for dwarfs, though this depends on the resolution and S/N of the data in question.

6. SUMMARY AND CONCLUSIONS

We have investigated systematic effects on the O abundances derived from the 6300 Å [O I] line and 7774 Å O I triplet in solar-type stars. Our 7774 Å solar intensity spectra confirm the observed flatness of Altrock's (1968) equivalent width–μ relation relative to LTE calculations. TLLS' NLTE models better reproduce the morphology of the equivalent width–μ relation. Still, our *flux*-based solar 7774 Å equivalent widths, which agree very well with other measurements (e.g., EAGNLT93), yield an O abundance perfectly consistent with both the accepted value and that implied by the forbidden line.

For the metal-rich ([Fe/H]≳−0.5 say) stars studied here, good quality parameters are available. In our opinion, their small errors have negligible effects on the relative 6300 and 7774 Å O abundances. This conclusion does not hold for equivalent width errors. Flux-based measurements (obtained using the same equipment as for stellar spectra) of the solar 6300 Å [O I] line indicate an equivalent width of ~5.8 mÅ.

However, we measure a much larger value from the KFBT atlas. The same effect is seen for the 7774 Å triplet. Therefore, reliance on an *assumed* solar abundance or atlas data to perform normalization may introduce large (~0.2 dex or more) systematic errors. As shown in Paper V, there are systematic differences (not discussed now since they are not seen here) in different author's 7774 Å equivalent widths for metal-rich stars. Literature results suggest large discrepancies (~0.2 dex in abundance) also exist in the stronger (compared to dwarfs) [O I] lines in giants.

A range of 0.17 dex in the 7774 Å log gf values is seen in recent abundance analyses. This introduces, *ceteris paribus* (not always the case in abundance analyses), an equivalent uncertainty in the derived LTE abundance. Various van der Waals damping "constants" in recent 7774 Å O I abundance analyses produce differences ~0.15 dex in derived absolute abundances. These effects may or may not result in genuine systematic errors in the [O/H] values, depending on how normalization to solar is handled. Model atmosphere differences do not seem to affect derived 6300 Å [O I] abundances (as expected). However, there is a possibility that systematic differences of ~0.10 dex in the derived 7774 Å abundances may be caused by differences in model atmospheres (or analysis software).

Unfortunately, large errors may be attached to *both* the forbidden and permitted line O abundances. The various uncertainties noted above are not necessarily independent (nor random); rather, there is dependence on the method of normalization of the stellar abundances to solar. Using existing and new data, we compare 6300 and 7774 Å O abundances for a sample of metal-rich dwarfs. Our analysis minimizes, to the extent possible, the uncertainties noted above. At low $T_{\rm eff}$, we see no significant trend or offset of the 6300 and 7774 Å O abundances. For $T_{\rm eff}\gtrsim 6300$ K, our own data (and that of Clegg *et al.* 1981) indicate that the permitted line O abundances are significantly larger than those from the forbidden line. We interpret this as the onset of previously known genuine NLTE effects for early-type stars. The exact boundary between the two regimes, however, remains fuzzy and we cannot definitively exclude that differences of 0.05–0.10 dex exist at ~6200 K.

Our results conflict with those of NE92 and those inferred from the NE92 data reanalysis, both of which indicate a significant offset between the 6300 and 7774 Å O abundances at all $T_{\rm eff}$. The difference rests solely in the 7774 Å abundances and seems to originate in either the model atmospheres, software, or data. The trend of increasing Δ[O/H] with declining [Fe/H] persists in our NE92 data reanalysis. No such trend is evident in the non-NE92 data, but the range in [Fe/H] is small. Such a trend is seemingly at odds with the NLTE calculations of Takeda (1994) and TLLS and with the empirical evidence suggesting no significant difference between 7774 Å abundances of halo dwarfs and 6300 Å abundances of both metal-poor giants and dwarfs. We again suggest the explanation may be differences in model atmospheres, analysis software, or raw data (e.g., equivalent widths) and not atmospheric inhomogeneities. All the various uncertainties we have mentioned may mask or exaggerate alleged systematic effects of NLTE or inhomogeneities. All we can say is, for the non-NE92 data having $T_{\rm eff}\lesssim 6200-6300$ K, our specific analysis either indicates no significant differences between the 6300 and 7774 Å abundances or has somehow (perhaps spuriously?) removed them. Finally, literature results lead us to question the notion that the 6300 Å forbidden line O abundances are more reliable than their 7774 Å counterparts. Clearly, much remains to be done before stellar O abundances can be derived with greater confidence.

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